Grand Unified Model of Accretion Disks: The Sub-Keplerian Paradigm[a]

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In the 1970s, the standard accretion disk models were constructed[1,2] to largely explain observations from the binary systems. In these systems, angular momentum supplied at the outer edge is necessarily Keplerian. Viscosity drives the inflow by removing angular momentum outwards and keeping the entire disk Keplerian in the process. Since then these binary disk models are being used also to explain big blue bump observed in the continuum of active galaxies and quasars and with some success[3]. Occasionally, one invokes additional components along with the standard thin disks, such as corona, warm absorbers, etc. in order to explain continuum as well as variable components of X-rays and γ-rays. There are several recent observations of almost zero time-lag correlated variabilities between X-rays and optical[4] which cannot be explained by simple Keplerian disk models. Temporal variation of line profiles from objects, such as, ARP102B and 3C390.3 is impossible to explain by using axisymmetric disk models[5]. Recent HST observation of M87 shows clear evidence of non-axisymmetry in the ionized disk around the black hole and the association of the spiral shock in NGC4258 with the accretion disk cannot be ruled out. These examples suggest the existence of large scale spiral shock waves in both M87 and NGC 4258[6]. It is also generally believed that the radiation from our own galactic center is most likely coming from a low efficiency, quasi-spherical, accretion flow.

That the disks need not be of 'standard' type was sensed by theoreticians even in late '70s and throughout the '80s. Thick accretion disk, transonic accretion disk and slim accretion disk models (For a general discussion and references, see Chakrabarti[7]) came about. In thick disks, angular momentum is assumed to be almost constant but the radial motion is ignored. In transonic disks, the flow is thin but the radial motion is included. In slim disks, matter is allowed to pass through the inner sonic point, thus improving on the standard disk model. However, in all these models, unsuccessful attempts were made to match the flow with *Keplerian disks* at some distance and the disk structure depended strongly upon the matching radius and other parameters invoked.

This intrinsic problem with these theoretical models, as well as problems in explaining a large number observations with Keplerian disks, particularly when applied to active galaxies, disappear with the realization that the accretion disks in active galaxies need not be Keplerian anywhere including the outer boundary! The outer boundary condition here is completely different from that of the binary systems, since matter is largely supplied by winds from

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mass lossing and colliding stars in random motion. Matter could lose most of its angular momentum before it brings itself together to form an accretion disk.

After the matter starts with highly sub-Keplerian angular momentum, its subsequent behaviour depends strongly upon the accretion rate and the viscosity in the flow. If the accretion rate is small enough, the flow passes through the outer sonic point (just as a Bondi flow) and remains supersonic before falling onto a black hole. If the accretion rate is high, matter would pass through the inner sonic point[8−9]. This description is valid if the entropy remains almost constant, i.e., the viscosity is small enough. Even when the flow starts with small entropy, some entropy could be generated at a shock or in the flow by viscosity which then allows the flow to pass through the inner sonic point as well[10−12]. If the entropy is higher (for a given accretion rate) it is likely that strong winds may be formed from flows with positive energy[9,11]. Except when the viscosity is high, the flow radiates with a very low efficiency as in a Bondi flow as discussed in these works.

Contrary to a Newtonian star, a black hole has no hard surface. If the flow is unable to lose angular momentum efficiently, the centrifugal barrier causes the flow to have a shock close to the black hole[7−12]. The postshock flow is the boundary layer equivalent of a black hole accretion. This is clearly the case when the viscosity is small enough. The postshock flow has all the features of a thick accretion disk only more self-consistent since the radial motion is also included[11]. The preshock flow is mainly advected towards the black hole, just as a Bondi flow, but the immediate post-shock flow is rotationally dominated as in a Keplerian disk. Further on, the flow picks up radial motion and supersonically enters into the black hole. If the viscosity is high (typically, if the α parameter[1] is larger than about 10^{-2}) the *stable* shock disappears and the disk eventually becomes Keplerian[10] except close to the boundaries.

Fig. 1(a-b): Mach Number (Y-axis) as a function of logarithmic radial distance (X-axis) for viscous isothermal flows. In (a), a weak shock is present ($\alpha = 0.01$). In (b) with $\alpha = 0.02$, the shock disappears. Out of two choices (arrowed curves), the one passing through the inner sonic point is preferred due to higher dissipation.

Fig. 1(a-b), adapted from Chakrabarti (1990) which solves the fully viscous, isothermal flows shows this behaviour. This prediction is verified by numerical simulation of viscous flows[12]. Fig. 2(a-b) shows the time variation (curves drawn at intervals of $1000GM/c^3$) of the Mach number and the angular momentum distribution in a viscous ($\alpha = 0.1$) flow which is sub-Keplerian at the outer boundary. Here the angular momentum is transported more efficiently in the post-shock flow and increasingly higher centrifugal barrier pushes the shock further out making it weaker in the process (2a) and making the disk shock free and quasi-Keplerian (2b). These highly viscous, shock-free, quasi-Keplerian solutions self-consistently pass through the inner sonic point. If the viscosity is very small, a weak shock can survive[10,12] and the angular momentum distribution remains sub-Keplerian everywhere except close to the marginally stable orbit where it is super-Keplerian. The dotted curve in Fig. 2a is the shock in the inviscid flow.

Fig. 2(a-b) Time evolution of Mach number (a) and angular momentum (b) variation as a function of logarithmic radial distance in a viscous flow.

Fig. 3: Composite disk model around a black hole with sub-Keplerian outer boundary condition and height dependent viscosity.

We thus notice that one may have a thick, thin, slim or transonic (with or without shocks) disk from an initially sub-Keplerian inflow at large distance depending upon accretion rate and viscosity. Based on this experience, in order to explain observations across the electromagnetic spectrum, a generic

model for the accretion disk could be built (Fig. 3). A disk of this kind would form if there is a significant variation of viscosity in the vertical direction inside the disk. Higher viscosity on the equatorial plane produces an optically thick standard Keplerian disk, which is vertically flanked by warm, optically thin halo of low angular momentum gas. The halo forms a standing shock close to the black hole ($\sim 10\ R_g$). The post-shock flow ($T_p \sim 10^{11}\ K$) heats up soft-photons coming from the disk to produce observed γ-rays. Such a model has the potential to explain most of the steady state as well as time dependent behaviour of the continuum and line emissions and is under active study[13].

In active galaxies, jets are also seen. It is generally assumed that in the absence of a binary companion (which is a sink of angular momentum in a binary system), jets has to carry away angular momentum of the disk. Various jet models are constructed in order to achieve this goal. It is to be remembered that the 'angular momentum' problem is present only in models which start with Keplerian flows at the outer boundary. In the sub-Keplerian paradigm such problems are not present. Even in the presence of high viscosity, the flow may have just enough (not excess!) *total* angular momentum to redistribute itself to form a quasi-Keplerian disk. In the case of low angular momentum flow, shear is strong only close to the black hole. Strong shear produces very strong toroidal field. In the gas pressure dominated hot disks (with $T_p > 4 \times 10^{10}\ K$) magnetic tension catastrophically brings the flux tubes close to the black hole axis[14], ejecting matter from the inner accretion disk in the form of jets. Thus the jets would be blobby, rather than continuous. This general feature may have been observed in detail in GRS 1915+105[15].

REFERENCES

1. Shakura, N.I. & R.A. Sunyaev. 1973. Astron. Astrophys. **24:** 337.
2. Novikov, I. & K.S. Thorne. 1973. in: Black Holes, eds. C. DeWitt and B. DeWitt (Gordon and Breach, New York).
3. Sun, W.H. & M.A. Malkan. 1989. Astrophys. J. **346:** 68.
4. Clavel, J. et al. 1990. Mon. Not. R. Astron. Soc. **246:** 668.
5. Chakrabarti, S.K. & P.J. Wiita. 1994. Astrophys. J. **434:** 518.
6. Chakrabarti, S.K. 1995. Astrophys. J. (March 10th, in press)
7. Chakrabarti, S.K. 1995. Physics Reports (to appear).
8. Chakrabarti, S.K. 1990. Theory of Transonic Astrophysical Flows (World Scientific, Singapore, 1990)
9. Chakrabarti, S.K. 1989. Astrophys. J. **347:** 365.
10. Chakrabarti, S.K. 1990. Mon. Not. R. Astron. Soc. **243:** 610.
11. Molteni, D., G. Gerardi & S.K. Chakrabarti. 1994. Astrophys. J. **436:** 249.
12. Chakrabarti, S.K. & D. Molteni. 1995. Mon. Not. R. Astron. Soc. **272:** 80.
13. Chakrabarti, S.K., L. Titarchuk, & D. Kazanas. 1995. (in preparation)
14. Chakrabarti, S.K. & S. D'Silva. 1994. Astrophys. J. **424:** 138.
15. Mirabel, I.F. & Rodriguez, L.F. 1994. Nature **371:** 46.